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Land use and climate change impacts on runoff and soil erosion at the hillslope scale in the Brazilian Cerrado

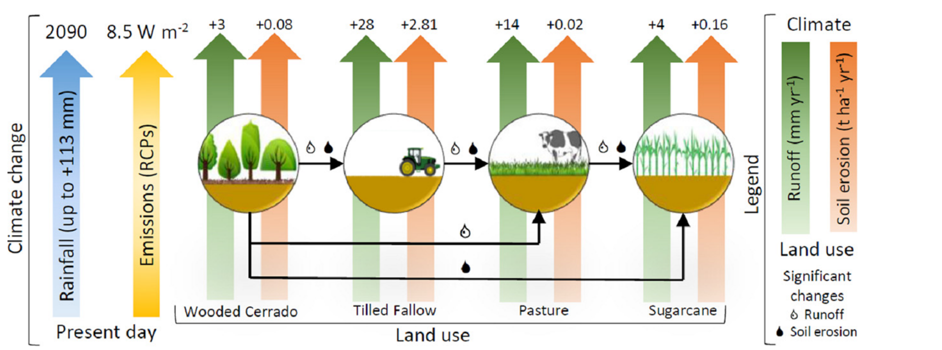
Jamil A.A. Anache [a,c,*], Dennis C. Flanagan [b,c], Anurag Srivastava [c], Edson C. Wendland [a]

[a] São Carlos School of Engineering (EESC), University of São Paulo (USP), CxP. 359, São Carlos, SP 13566-590, Brazil
[b] USDA-Agricultural Research Service, National Soil Erosion Research Laboratory, 275 S. Russell St., West Lafayette, IN 47907-2077, USA
[c] Department of Agricultural & Biological Engineering, Purdue University, USDA-ARS-NSERL, 275 S. Russell St., West Lafayette, IN 47907-2077, USA

HIGHLIGHTS

- Process-based models replace empirical ones when long-term observations are scarce.
- A process-based model effectively estimates runoff and soil erosion in Brazil.
- Land use influences on runoff and soil erosion rates in a tropical soil.
- Runoff and soil erosion responses to climate change are not significant.
- Agricultural land may reach conservation levels of an undisturbed tropical woodland.

GRAPHICAL ABSTRACT



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ABSTRACT

Land use and climate change can influence runoff and soil erosion, threatening soil and water conservation in the Cerrado biome in Brazil. The adoption of a process-based model was necessary due to the lack of long-term observed data. Our goals were to calibrate the WEPP (Water Erosion Prediction Project) model for different land uses under subtropical conditions in the Cerrado biome; predict runoff and soil erosion for these different land uses; and simulate runoff and soil erosion considering climate change. We performed the model calibration using a 5-year dataset (2012–2016) of observed runoff and soil loss in four different land uses (wooded Cerrado, tilled fallow without plant cover, pasture, and sugarcane) in experimental plots. Selected soil and management parameters were optimized for each land use during the WEPP model calibration with the existing field data. The simulations were conducted using the calibrated WEPP model components with a 100-year climate dataset created with CLIGEN (weather generator) based on regional climate statistics. We obtained downscaled General Circulation Model (GCM) projections, and runoff and soil loss were predicted with WEPP using future climate scenarios for 2030, 2060, and 2090 considering different Representative Concentration Pathways (RCPs). The WEPP model had an acceptable performance for the subtropical conditions. Land use can influence runoff and soil loss rates in a significant way. Potential climate changes, which indicate the increase of rainfall intensities and depths, may increase the variability and rates of runoff and soil erosion. However, projected climate changes did not significantly affect the runoff and soil erosion for the four analyzed land uses at our location. Finally, the runoff behavior was distinct for each land use, but for soil loss we found similarities between pasture and wooded Cerrado, suggesting that the soil may attain a sustainable level when the land management follows conservation principles.

* Corresponding author at: São Carlos School of Engineering (EESC), University of São Paulo (USP), CxP. 359, São Carlos, SP 13566-590, Brazil.
E-mail addresses: jamil.anache@usp.br (J.A.A. Anache), dennis.flanagan@ars.usda.gov (D.C. Flanagan), srivas42@purdue.edu (A. Srivastava), ew@sc.usp.br (E.C. Wendland).

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1. Introduction

The increase of soil erosion with time is linked to the intensification of land use for agricultural purposes worldwide. There is a strong relationship between land use, soil management, soil erosion and agricultural sustainability (Vanwalleghem et al., 2017). Additionally, nutrient residence time in cropland soil is likely to decrease as the soil is disturbed (Quinton et al., 2010). The representation of the water flow patterns in the soil (under natural and disturbed conditions) is a large topic of discussions and hillslope observations are needed to improve the performance of comprehensive models (Beven and Germann, 2013).

Although potential climate changes can influence runoff and soil erosion, the prediction technologies should include rill and interrill water erosion, try to account for the role of extreme events in the simulated processes, and include different crop rotations and land use change dynamics (Li and Fang, 2016). The low resolution scale from the General Circulation Models (GCMs) can be downscaled to generate stochastic future climate scenarios for runoff and soil erosion models (Jones and Thornton, 2013; Wilby et al., 2009). Additionally, the inclusion of prediction uncertainties would improve long-term assessments in runoff and soil erosion model frameworks (Kim et al., 2016).

The Brazilian Cerrado biome is the largest savanna area in South America, comprising 2,033,601 km^2. This region is part of the country's agricultural frontier due to the intense conversion from natural vegetation to pastureland and croplands, and is becoming a biodiversity extinction hotspot (Hughes, 2017; Lapola et al., 2013). Cultivated pasturelands occupy approximately 1,120,000 km^2 in Brazil, and São Paulo is one of the Brazilian states that includes large areas of cultivated pastureland that are suitable for sugarcane production (Alkimim et al., 2015). As Brazil is the world's largest sugarcane producer and due to increasing biofuel demand, a huge extension of the Cerrado biome was converted to this crop (Loarie et al., 2011). Apparently, the substitution of pasture with sugarcane increases runoff and soil erosion due to the tillage disturbance and associated decrease in soil quality, however, more observations are needed to understand this behavior during a longer period (Youlton et al., 2016b).

An initial study to measure runoff and soil erosion in a Cerrado sensu stricto area (undisturbed tropical woodland or wooded Cerrado) indicated that <1% of the rainfall was converted into runoff and the soil loss was around 0.1 t ha^{-1} yr^{-1} (Oliveira et al., 2015). At the same site, tilled fallow conditions generated runoff that was approximately 20% of the rainfall and the soil erosion rates were >10 t ha^{-1} yr^{-1}.

In general, short period experimental studies in Brazil do not explain the long-term variability of runoff and soil erosion processes (Anache et al., 2017). In addition, climate extremes may affect agricultural sites and, consequently, their runoff and soil erosion rates (Lapola et al., 2013; Li and Fang, 2016). Thus, critical research considering hillslopes with different land use managements is needed to predict the responses of runoff and soil erosion to a changing climate.

The Curve Number (CN) method developed by the USDA-NRCS (2004) is a popular alternative to predict the overland flow in a simple way according to the rainfall depth of a given event. However, runoff estimates using the CN method in Brazil are inaccurate (Oliveira et al., 2016). In general, many erosion models do not include runoff as a factor, and empirical models, such as the Universal Soil Loss Equation (USLE) and the CN method, are not likely to be applied with no restrictions in Brazil. These problems can occur because the empirical models' input parameters are based on long-term field observations performed within the United States, under their environmental conditions, where the models provide satisfactory performances (Kinnell, 2017).

Process-based models, such as the Water Erosion Prediction Project (WEPP) (Nearing et al., 1989; Flanagan et al., 2007), can be applied to a wider range of conditions, and are powerful tools for estimating runoff and soil erosion. The WEPP model was first released publicly in 1995 by the United States Department of Agriculture – Agricultural Research Service (USDA-ARS) as a new generation of water erosion prediction technology to be used as a planning and management tool in soil and water conservation (Flanagan et al., 2001). WEPP takes into consideration water infiltration, surface runoff, plant growth, residue decomposition, flow hydraulics, tillage disturbance, residue management, soil consolidation, and erosion mechanics. The WEPP model has been shown to be efficient in estimating runoff and soil loss, and also enhances the results with the capability to predict both temporal and spatial distributions of soil erosion in a hillslope or a small watershed (Pandey et al., 2016; Tiwari et al., 2000).

The purpose of this study was to better understand how natural and agricultural land uses govern runoff and soil loss under subtropical Brazilian conditions considering future climate scenarios. We aimed to (i) calibrate and validate the WEPP model for four land uses (wooded Cerrado, fallow, pasture, and sugarcane) under subtropical conditions for a specific site inside the Cerrado biome; (ii) predict baseline runoff and soil erosion for these different land uses using stochastic climate generator inputs; and (iii) simulate runoff and soil erosion considering possible future climate change scenarios.

2. Material and methods

2.1. Study area and experimental design

The study area is located in the Arruda Botelho Institute (IAB), Itirapina, central area of the state of São Paulo, Brazil (latitude 22°11′5″ S, longitude 47°51′11″W, elevation 790 m a.m.s.l.). It was divided into two sites: site 1 had plots containing three different agricultural land uses with three replicates each (pasture, sugarcane, and tilled fallow without plant cover); and site 2 had plots under undisturbed woodland typical of the central area of Brazil (Cerrado sensu stricto also known as wooded Cerrado) in three replicates (Fig. 1). The climate in the study area is humid subtropical (Cwa, Köppen classification system). The average annual temperature and rainfall are 21.5 °C and 1486 mm yr^{-1}, respectively, with hot and rainy summers (October–March, mean temperature of 23.6 °C and 77% of annual rainfall) and dry winters (April–September, mean temperature of 19.5 °C and 23% of annual rainfall) (Alvares et al., 2014; Cabrera et al., 2016). The soil is classified as Quartzipsamments (Oliveira et al., 2016), an entisol, with a sandy texture, covering around 15% of the Cerrado biome area.

The wooded Cerrado region in Brazil is composed of tropical woodland vegetation in a continuous herbaceous layer. The trees do not form a continuous canopy, but the Cerrado has a dominant woody component of six to seven meters high and some trees reaching up to 12 m (Alberton et al., 2014). The experimental plots at site 1 were covered by three different land uses: (i) Signalgrass (*Brachiaria decumbens*) vegetation (20 continuous years) in the pastureland, used for cattle raising, with the canopy height varying between 5 and 30 cm. Cattle grazing was in a 30-day rotation of 10 animals (420 kg each) per hectare for 5 days; (ii) Sugarcane (*Saccharum officinarum*) plantation established on October 2011 was contour planted on beds with a 1.5 m spacing, with the plant canopy reaching at least 2 m in height. The soil was ploughed to a 30 cm depth, and furrows were formed with a 20 cm depth on the contour (Youlton et al., 2016b). Sugarcane was harvested every year in November; (iii) Bare soil plots were maintained in a tilled fallow condition by glyphosate application and manual tillage (Oliveira et al., 2015).

2.1.1. Runoff and soil erosion observations

Experimental plots of 5 m width and 20 m length, with a 9% uniform slope gradient were used for the field observations (Fig. 1). A metallic collector placed at the end of each plot carried runoff water and eroded sediments to a storage tank (Youlton et al., 2016a). The runoff volumes were determined using the storage tanks' water level-volume calibration curves. Runoff and sediment (well-stirred samples) were collected from the storage tanks. Overland flow and soil loss rates were measured after a group of events under the wooded Cerrado, pasture, sugarcane,

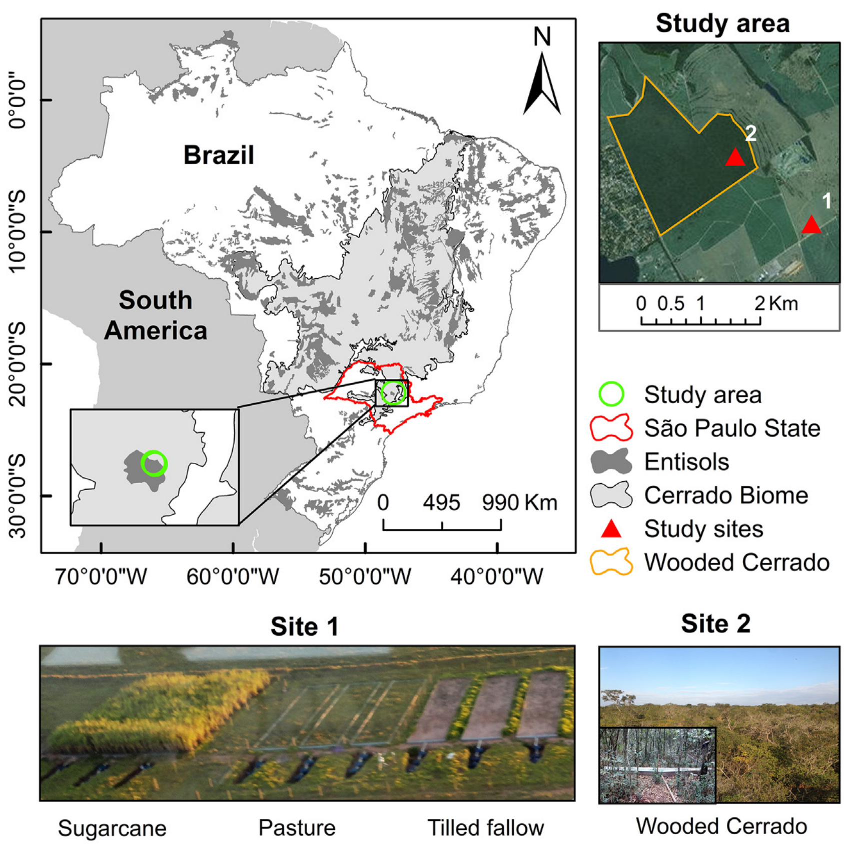

Fig. 1. Location of study sites, Cerrado biome borders, entisols' distribution in Brazil, and experimental design, where site 1 contains the plots with agricultural landuses (pasture, sugarcane, and tilled fallow without plant cover) and site 2 contains the plots with wooded Cerrado.

and bare soil (tilled fallow conditions) plots, with three plot replicates for each treatment. The sediment concentrations of the runoff samples were determined gravimetrically in the laboratory, as well as the dry mass of the soil retained in the runoff collector that did not reach the storage tanks. The total soil erosion from each plot was calculated by the sum of the product between sediment concentration and runoff volume with the dry mass of the soil retained in the rainfall collector (Oliveira et al., 2015; Youlton et al., 2016b).

2.1.2. Meteorological observations

Meteorological variables (precipitation, relative humidity, temperature, solar radiation, wind speed and direction) were monitored every day at 10-minute intervals during the 5-year period (2012–2016). The weather station was located inside the experimental area with agricultural land uses (site 1), and it was equipped with a data acquisition system with real time data sharing.

2.2. The WEPP model

The WEPP model is a process-based, distributed parameter, and continuous simulation erosion prediction computer program that simulates the major processes of overland flow, sheet and rill erosion, and erosion from small channels, such as ephemeral gullies (Flanagan et al., 2012). The model input parameters are divided into four main components: climate, soil, plant growth and management, and topography. WEPP inputs are described by Flanagan et al. (2001) and we summarize them here: For continuous simulations, the climate inputs are organized on a daily basis and they can be observed or generated to drive the runoff and erosion processes within WEPP. Breakpoint climate input format is typically used during the model calibration and validation phases. For conservation planning or climate change impact simulations, WEPP utilizes CLIGEN (Nicks et al., 1995), a weather generator that creates climate datasets based on long-term weather station statistics containing the following information: daily precipitation depth, storm duration, rainfall intensity, maximum temperature, minimum temperature, dew point temperature, solar radiation, and wind velocity and direction.

The WEPP soil component predicts the effects of soil tillage, sealing, crusting, and consolidation, and governs the water infiltration rates into the soil and the erodibility properties. The main soil input parameters are the baseline effective hydraulic conductivity, rill and interrill erodibilities, and critical hydraulic shear stress. Other input soil properties (texture, organic matter, Cation Exchange Capacity, rock fragments) can be described in layers to a maximum depth of 1.8 m. Reducing the uncertainties in estimating soil physical and hydrological parameters is essential when operating the WEPP erosion prediction model.

The plant/management component of WEPP simulates planting, growth, and harvest of crops or other vegetation, and allows the user to describe a large number of cropping and management operations, as well as the interaction of management and environment in processes involved in simulation. These include specifying dates and types of tillage operations and associated tillage parameters, dates of planting of crops and crop growth parameters, dates of harvesting of crops, dates of residue management (addition, removal, burning, shredding, etc.) and associated parameters, and dates, types, and scheduling of irrigation applications.

Finally, the topographic characteristics of the hillslope profiles are entered through the slope component inputs. These require some landscape information such as slope orientation (aspect), slope length, and slope steepness at points down the hillslope. Within a calibration procedure, the climate and slope inputs are typically fixed components, which are not changed during the optimization process.

In the context of the present study, the processing steps to calibrate, validate, and simulate using the WEPP model are presented in Fig. 2.

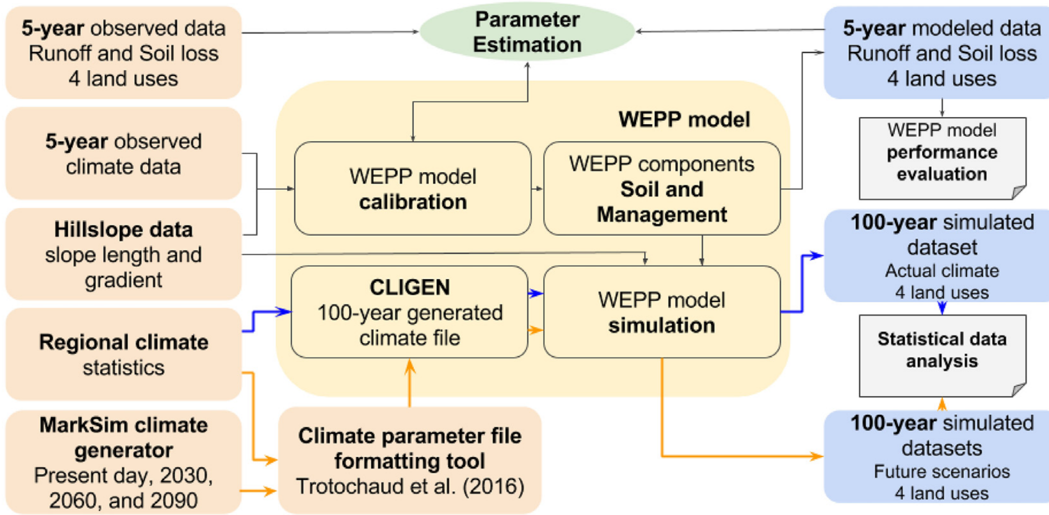

Fig. 2. Workflow chart containing the steps performed for WEPP model simulations.

Details about the governing equations of the WEPP model can be found in Flanagan and Nearing (1995), Flanagan et al. (2001), and Nearing et al. (1989).

2.3. WEPP model calibration and validation

WEPP was run in continuous simulation mode using the meteorological data observed at the experimental field station for five years (2012–2016), with breakpoint precipitation climate inputs. The following critical parameters (Flanagan et al., 2012) were selected within the model components to perform the calibration: soil component (baseline critical shear, baseline effective hydraulic conductivity, baseline interrill erodibility, and baseline rill erodibility); and management component (biomass energy ratio, maximum canopy height, maximum root depth, canopy cover coefficient, initial roughness; and initial interrill and rill cover). The soil component input required information about the particle size distribution, hydraulic conductivity, and density along the first meter of depth of the soil and the levels of organic matter content and Cation Exchange Capacity (CEC) for the soil in the study area (Table 1). The baseline erodibilities were calibrated using the observed soil loss values from the tilled fallow plots, and these were then applied in the other land use (wooded Cerrado, pasture, and sugarcane) simulations without changes. The other input parameters (plant growth, residue management, initial conditions, etc.) were adjusted for each land use separately. The definition of the parameters' bounds and initial values for the optimization are described in the next section. Additionally, the tilled fallow condition did not consider plant management inputs, as there was no vegetation cover.

The WEPP model can generate output for different time-scales (event, monthly, and annual basis). As the observed data consisted of cumulative samples of overland flow, we opted to use the seasonal values (annual rainy and dry seasons) to calibrate and validate the model. The calibration was performed using the observations from 2012 to 2014, and the validation considered the observations from 2015 to 2016.

Model performance was evaluated grouping all land uses using the following statistical metrics: R^2 (coefficient of determination); NSE (Nash-Sutcliffe Efficiency coefficient); RSR (root mean square error observations standard deviation ratio); and PBIAS (percent bias) (Gupta et al., 2009; Moriasi et al., 2007). Considering rainy and dry seasons,

Table 1
Soil texture and properties at 14, 30, 60, and 90 cm depths at the study site.

Depth	Particle sizes (mm)							
	Sand						Silt	Clay
	VC 2–1	C 1–0.5	M 0.5–0.25	F 0.25–0.10	VF 0.10–0.05	T 2–0.05	0.05–0.002	<0.002
(cm)	g kg^{-1}							
0–14	16	22	158	349	333	879	33	88
30	5	31	223	518	87	865	34	101
60	5	32	224	494	90	844	30	126
90	4	31	227	485	90	836	39	125

	Other properties				
	CEC	OM	BD	PD	HC
(cm)	mmol dm^{-3}	g kg^{-1}	g cm^{-3}	g cm^{-3}	mm h^{-1}
0–14	40.3	38	–	–	–
30	–	–	1.64	2.64	147.31
60	–	–	1.53	2.65	117.01
90	–	–	1.52	2.65	129.34

VC – very coarse; C – coarse; M – medium; F – fine; VF – very fine; T – total; CEC – cation exchange capacity; OM – organic matter; BD – bulk density; PD – particle density; HC – hydraulic conductivity.

28 observed points (n1) were used for calibration (from rainy season 2012 to rainy season 2015), and 16 points (n2) for validation (from dry season 2015 to rainy season 2016).

2.3.1. Parameter estimation tool

The Parameter Estimation (PEST) tool is a software package for parameter estimation and uncertainty analysis of complex environmental and other computer models (Doherty, 2015), and was used here to optimize the critical parameters during the calibration. PEST allows setting an upper and a lower limit for each parameter to be optimized, in order to avoid equifinality during the model calibration (Jetten and Maneta, 2011). The parameters' bounds and initial values were defined according to information in the WEPP model management and soil databases (Elliot et al., 1989; Nearing et al., 1989), considering soils with similar properties to the study area and corresponding land uses and management procedures to the conditions evaluated here. However, the ranges used for maximum canopy height and maximum root depth were based on literature review (Alberton et al., 2014; Canadell et al., 1996; Garcia-Montiel et al., 2008; Oliveira et al., 2005; Youlton et al., 2016b). We adopted the Shuffled Complex Evolution approach (SCE) (Duan et al., 1993) for an effective and efficient global error minimization of the WEPP model parameter estimates.

2.4. WEPP model simulation

Generated climate inputs were used to drive the runoff and soil erosion predictions during the simulation phase. These inputs were based on long-term weather station statistics to run the weather generator (CLIGEN) (Flanagan et al., 2007). CLIGEN generated 100-year sequences of daily weather values to run the WEPP model, which was previously calibrated and validated to the location of the present study. This allowed for long-term assessments of the runoff and soil erosion variability at our location with a suitable weather generator for water resources applications (Mehan et al., 2017).

2.4.1. Simulations with present climate

The historically observed climate to parameterize CLIGEN were obtained from the Luiz de Queiroz College of Agriculture (ESALQ-USP) climate station in Piracicaba, Brazil, established in 1917 (latitude 22°42′30″ S, longitude 47°38′30″W, elevation 546 m a.m.s.l.). The required parameters to build the climate baseline were monthly statistics for precipitation (1917–2016), storm duration and peak intensity (1997–2016), air and dew point temperatures (1917–2016), solar radiation (1978–2016), and wind speed and direction (1943–2016) (Singh et al., 2017). This station has similar climate conditions of the study area in terms of precipitation and temperature and has a long-term 100 years of observations (1917–2016) for a majority of the parameters.

2.4.2. Simulations with projected climates

Recently, a simpler and faster tool to obtain a downscaled future climate data from multiple General Circulation Models (GCMs) for multiple locations has been developed (Trotochaud et al., 2016). The MarkSim DSSAT is a weather generator based on a Markov model fitted to the GCMs outputs, using 720 weather classes (worldwide) that define the Markov model coefficients to generate daily data. This stochastic downscaling was used to create climate information for the study area containing 50 replicates for present day (baseline) and each projected year (2030, 2060, and 2090). Future climate was averaged from 17 GCMs (BCC-CSM 1.1, BCC-CSM 1.1 m, CSIRO-Mk3.6.0, FIO-ESM, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, GISS-E2-H, GISS-E2-R, HadGEM2-ES, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC-ESM, MIROC-ESM-CHEM, MIROC5, MRI-CGCM3, and NorESM1-M), considering different emissions levels according to the Representative Concentration Pathways (RCP). The downscaled variables were rainfall depth, maximum temperature, minimum temperature and solar radiation, all of them generated on a daily basis, for the selected location, with a maximum spatial resolution of 2.8°.

Four levels of RCP scenarios considered in this study were: RCP 2.6 (by 2100, an increase of 2.6 W m^{-2} solar radiation and a CO_2 peak concentration of 490 ppm); RCP 4.5 (by 2100, an increase of 4.5 W m^{-2} solar radiation and a CO_2 stabilized concentration of 650 ppm); RCP 6.0 (by 2100, an increase of 6.0 W m^{-2} solar radiation and a CO_2 stabilized concentration of 850 ppm); and RCP 8.5 (by 2100, an increase of 8.5 W m^{-2} solar radiation and a CO_2 concentration reaching 1370 ppm) (Li and Fang, 2016).

After obtaining the projected future climate information from MarkSIM, the data were processed with the Trotochaud et al. (2016) tool, providing the parameter (.par) files to be used with the CLIGEN weather generator (a WEPP component). The Trotochaud et al. (2016) tool is Visual Basic (VBA) code within a Microsoft Excel spreadsheet, which automatically imports, analyzes, aggregates, and calculates the necessary statistics for running CLIGEN. The future scenarios were based on the fifth assessment report (AR5) published by the Intergovernmental Panel on Climate Change (IPCC) using a multi-model approach (IPCC, 2014; Jones and Thornton, 2013; Wilby et al., 2009). The 100-year datasets were stochastically generated with the modified CLIGEN parameter files for future climate scenarios. The procedure uses historical data (rainfall intensity and wind speed and direction) to reconstruct typical weather patterns, however, it uses future climate projections of temperature, precipitation, and solar radiation to add the potential climatic changes estimated using the GCMs according to the IPCC-AR5. Finally, the WEPP model was run again using the new climate input files, which represented the future scenarios.

It was possible to group the changes in predicted rainfall, runoff, and soil erosion according to their trends by comparing the differences (Δ) in the WEPP annual output results using the future and present (baseline) climate inputs (Nearing et al., 2004). There were two options for each simulated variable: increasing or decreasing rainfall, runoff, and soil erosion; making eight possible combinations (Groups) that classified the simulations using the projected future climate inputs.

2.5. Data analysis

We found that the runoff and soil erosion data did not violate normality assumptions within a 99% confidence interval. Therefore, ANOVA was applied to compare the null and alternative hypothesis, that is, equality of rainfall, runoff, and soil erosion distribution functions between the four treatments (land use or climate scenarios) versus difference in distribution functions between at least two treatments. Additionally, the multiple comparisons between treatments were performed using the Tukey test (Montgomery, 2008).

Table 2
Calibrated WEPP model target parameters.

Model component	Parameter	Unit	Land use			
			Fallow	Wooded Cerrado	Pasture	Sugarcane
Soil	cs	Pa	0.68	3.36	4.04	3.36
	ke	mm·h^{-1}	67.40	149.93	17.15	82.21
	ki	Kg·s·m^{-4}	3.46E + 06	3.46E + 06	3.46E + 06	3.46E + 06
	kr	10^3 s·m^{-1}	22.79	22.79	22.79	22.79
Management	beinp	Kg/MJ	–	2.44	12.03	0.85
	hmax	m	–	6.01	0.10	3.12
	rdmax	m	–	6.04	0.10	0.51
	bb	%	–	30.22	6.85	26.04
	rrinit	cm	–	3.05	2.52	2.22
	cov	–	–	40.24	56.87	82.99

Parameter descriptions: cs – critical shear; ke – effective hydraulic conductivity; ki – interrill erodibility; kr – rill erodibility; beinp – biomass energy ratio; hmax – maximum canopy height; rdmax – maximum root depth; bb – canopy cover coefficient; rrinit - initial roughness; cov – initial rill and interrill cover.

Table 3
Field observations and WEPP estimations for runoff and soil erosion by season.

Land use	Year	Season	Rainfall (mm)	Runoff (mm)		Soil loss ($t\cdot ha^{-1}$)	
			Observed	Observed	Predicted	Observed	Predicted
Fallow	2012	Rainy	963	117	70	9.29	14.96
	2012	Dry	129	14	4	1.36	1.22
	2012/2013	Rainy	1293	173	94	12.76	13.70
	2013	Dry	91	3	0	1.78	0.00
	2013/2014	Rainy	1053	50	173	7.32	16.53
	2014	Dry	126	1	10	1.27	0.73
	2014/2015	Rainy	1144	136	133	14.79	20.25
	2015	Dry	236	19	20	2.61	1.39
	2015/2016	Rainy	1403	153	155	23.37	17.79
	2016	Dry	72	0	0	0.68	0.00
	2016	Rainy	432	23	33	5.42	3.31
Wooded Cerrado	2012	Rainy	963	4	0	0.21	0.00
	2012	Dry	129	0	0	0.01	0.00
	2012/2013	Rainy	1293	2	0	0.11	0.00
	2013	Dry	91	0	0	0.00	0.00
	2013/2014	Rainy	1053	1	2	0.06	0.10
	2014	Dry	126	0	0	0.00	0.00
	2014/2015	Rainy	1144	2	0	0.15	0.00
	2015	Dry	236	0	0	0.02	0.00
	2015/2016	Rainy	1403	2	45	0.12	0.08
	2016	Dry	72	0	0	0.01	0.00
	2016	Rainy	432	0	0	0.03	0.00
Pasture	2012	Rainy	963	22	17	0.12	0.01
	2012	Dry	129	1	0	0.01	0.00
	2012/2013	Rainy	1293	48	20	0.06	0.03
	2013	Dry	91	0	0	0.01	0.00
	2013/2014	Rainy	1053	19	72	0.07	0.10
	2014	Dry	126	0	6	0.00	0.01
	2014/2015	Rainy	1144	61	46	0.10	0.03
	2015	Dry	236	6	1	0.03	0.00
	2015/2016	Rainy	1403	62	68	0.13	0.02
	2016	Dry	72	0	0	0.01	0.00
	2016	Rainy	432	6	8	0.02	0.01
Sugarcane	2012	Rainy	963	39	34	1.07	1.93
	2012	Dry	129	1	0	0.02	0.00
	2012/2013	Rainy	1293	15	9	0.50	0.18
	2013	Dry	91	0	0	0.00	0.00
	2013/2014	Rainy	1053	5	11	0.21	1.48
	2014	Dry	126	0	0	0.01	0.00
	2014/2015	Rainy	1144	11	13	0.90	0.25
	2015	Dry	236	0	0	0.03	0.00
	2015/2016	Rainy	1403	8	49	0.18	0.11
	2016	Dry	72	0	0	0.01	0.00
	2016	Rainy	432	1	0	0.22	0.00

3. Results and discussion

3.1. WEPP calibration and validation

In comparison to field observations from 2012 to 2014, WEPP calculated runoff and soil loss after the optimization procedure using the SCE approach during the model calibration. Using the optimized parameters for each land use (Table 2) WEPP produced results for the hillslopes representing the field erosion plots.

The observed and WEPP-predicted runoff and soil loss during the calibration and validation periods were computed on a seasonal basis (Table 3). Additionally, the WEPP model showed some inaccuracies in the prediction of runoff and soil loss in the wooded Cerrado through the years due to the very low values of runoff typical of this type of land use. However, looking at the estimated mean values, they agreed well with the field observations (Table 3, Table 4, and Fig. 3).

The model performance evaluation for the runoff and soil erosion estimations is given by the statistical metrics (Table 4) following the Moriasi et al. (2007) guidelines. The runoff and soil erosion estimates showed satisfactory results during the calibration ($n1 = 28$) and validation phases ($n2 = 16$). According to the PBIAS results, the WEPP model underestimated runoff and overestimated soil erosion in the studied hillslopes for the whole observation period (Gupta et al., 1999). The R^2 is not sensitive to the additive and proportional differences between observed and simulated data, and it represents only the linear relationship between two variables (Yang et al., 2014). Therefore, higher PBIAS for soil erosion contrast with the good linear correlation addressed by the R^2 in comparison with runoff evaluation, which presented an opposite result.

Scatter plots ($n = 44$) containing simulated versus observed data (Fig. 3) showed that the soil erosion estimates had a better correspondence to the observed data than the runoff predictions. The NSE

Table 4
WEPP model performance evaluation to predict runoff and soil erosion considering all land uses.

Period	Runoff				Soil erosion			
	R^2	NSE	RSR	PBIAS	R^2	NSE	RSR	PBIAS
Calibration (2012–2014)	0.79	0.77	0.48	20%	0.92	0.64	0.60	−37%
Validation (2015–2016)	0.86	0.84	0.40	−35%	1.00	0.93	0.27	31%
All period (2012–2016)	0.77	0.79	0.46	4%	0.85	0.80	0.45	−11%

R^2 - coefficient of determination; NSE - Nash–Sutcliffe model efficiency coefficient; RSR – RMSE observations standard deviation ratio; RMSE – root mean square error; PBIAS – percent bias.

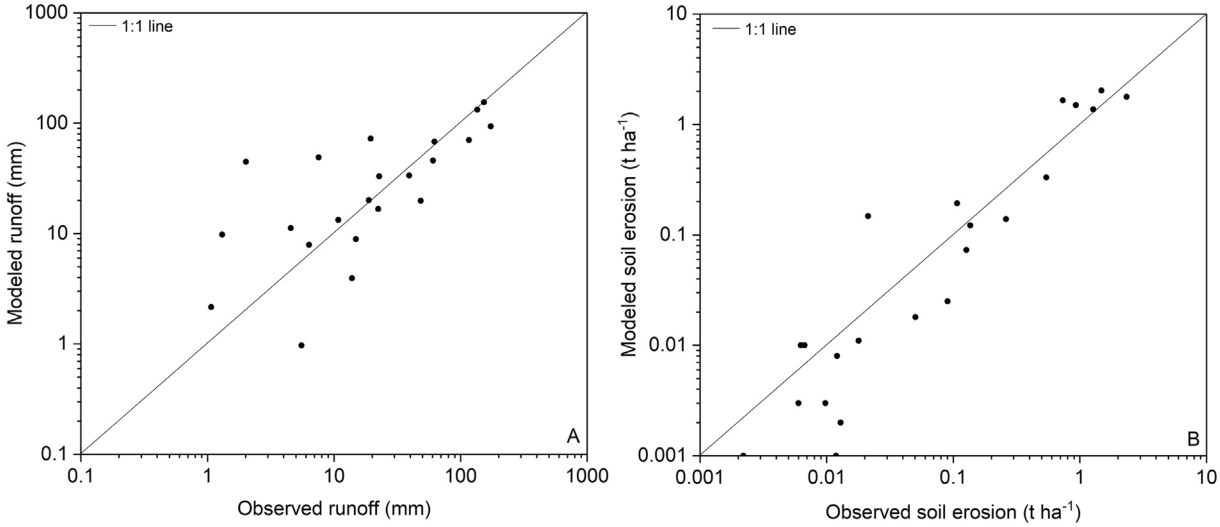

Fig. 3. Comparison between observed and WEPP calculated runoff (A) and soil erosion (B).

indicated that predicted soil loss was slightly closer to the 1:1 line than the runoff when observed and modeled datasets were plotted (Fig. 3, Table 4), however, both runoff and soil loss predictions were very good according to Moriasi et al. (2007). The RSR values, reflecting a normalized index of the RMSE, indicated that the WEPP model presented acceptable levels of error in its predictions in both the calibration and validation phases. The degree of collinearity between observed and predicted values expressed by a R^2 higher than 0.5 shows that WEPP predicted acceptable values for runoff and soil erosion (Moriasi et al., 2007). Therefore, the WEPP model adjusted to the input conditions found in the study area in Southeastern Brazil can be useful to delineate areas suitable for crop, pasture, and native vegetation, helping to maintain natural resources and to ensure the economic development of agricultural areas by finding sustainable ways to maintain production (Montgomery, 2007; Oliveira et al., 2015).

3.2. Runoff and soil erosion simulations

3.2.1. Simulations in different land uses

The WEPP model estimates of runoff and soil loss are presented for each land use simulated at the hillslope scale (Fig. 4) and significant differences between the four treatments outcomes were found (P value <0.05). The datasets generated during the WEPP simulations in different land uses are available as supplementary material (S1). For the sugarcane simulation, we observed that the higher values for both runoff and soil loss corresponded to the years when the plants were removed and re-planted, causing higher levels of disturbance in the soil. Nevertheless, after the first harvest, the residue (straw) left in the field reduced runoff and soil erosion, agreeing with field observations (Youlton et al., 2016a; Youlton et al., 2016b). Therefore, possible reductions in soil porosity, organic carbon content, and mean diameter of soil aggregates were expected, as well as an increase in the soil bulk density (Valim et al., 2016).

As expected, sugarcane had greater soil erosion rates than pasture and wooded Cerrado due to the higher soil disturbance during soil tillage and planting (Table 5). Sugarcane requires replanting every cycle (5–6 years), as well as harvesting and soil tillage every year, and consequently, the soil remains bare for several months (Martinelli and Filoso, 2008). The simulation results agreed with the fact that natural landscapes have lower runoff and soil erosion rates than agricultural land uses, and pasturelands tend to be more resistant to soil erosion than croplands (Anache et al., 2017; Auerswald et al., 2009; Guo et al., 2015; Montgomery, 2007). Overall, the observations and predictions using real (5-year observed breakpoint climate inputs) and CLIGEN-

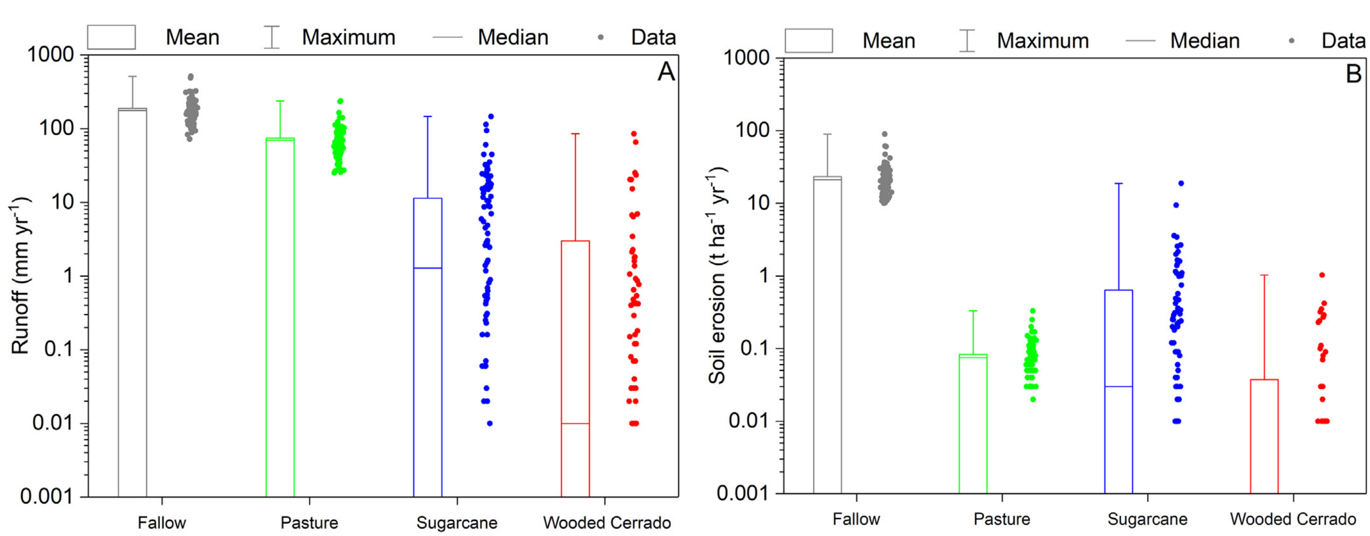

Fig. 4. Simulated runoff (A) and soil erosion (B) for different land uses using the 100-yr stochastically CLIGEN-generated climate derived from the long-term observed data.

Table 5
Observed (2012–2016), simulated (using 5-year breakpoint climate inputs), and predicted (using the 100-yr stochastically CLIGEN-generated climate derived from the long-term observed data) averages for runoff and soil erosion.

Data source	Land use	Rainfall (mm yr^{-1})	Runoff (mm yr^{-1})	Soil loss (t ha^{-1} yr^{-1})
5-year observations (2012–2016)	Wooded Cerrado	1388	2c	0.14c
	Fallow		138a	16.13a
	Pasture		45b	0.11c
	Sugarcane		16c	0.63b
5-year breakpoint WEPP simulations (2012–2016 climate inputs)	Wooded Cerrado	1388	9c	0.04c
	Fallow		144a	17.98a
	Pasture		48b	0.05c
	Sugarcane		23bc	0.79b
100-year generated climate WEPP predictions	Wooded Cerrado	1323	3c	0.04c
	Fallow		190a	23.37a
	Pasture		74b	0.08c
	Sugarcane		11c	0.64b

Identical lower case letters indicate no significant difference between means in the same column and data source by the Tukey means comparison test (P value >0.05).

generated (100-year generated climate inputs) exhibited similar behavior when comparing runoff and soil erosion rates from different land uses (Table 5).

Runoff rates under sugarcane and wooded Cerrado were similar. For soil erosion, only the fallow conditions presented a significantly different mean value compared to the other land uses (wooded Cerrado, pasture, and sugarcane). A significant similarity was observed between the pasture and wooded Cerrado soil erosion rates (Table 5). Thus, an increased runoff is not necessarily associated with an increased soil erosion (van Lier et al., 2005). Pasture presented high levels of runoff associated with low values for soil erosion, which were comparable to those found in the wooded Cerrado. This increased soil resistance to erosion under pasture is due to the fasciculated roots, which promote a greater soil aggregation (Nacinovic et al., 2014). A higher variability of runoff and soil erosion was estimated for the wooded Cerrado in comparison with the pasture under the same inputs (rainfall, topography, etc.) (Fig. 4). This fact may be explained by the seasonal variation of the soil coverage, evidenced by the high range of vegetation indexes and forest floor cover variation observed in this kind of natural landscape through the year (Ferreira and Huete, 2004; Oliveira et al., 2015). In addition, natural conditions tend to have a higher relative variability in runoff and soil erosion, because the variations increase as the rates decrease (Gómez et al., 2001; Nearing et al., 1999; Wendt et al., 1986).

3.2.2. Simulations using projected climate

The parameters extracted from historical observed climate data (1917–2016) combined with present day scenarios acquired from MarkSim weather generator resulted in present estimations for rainfall, runoff, and soil erosion for the different land uses (Table 6). MarkSim's present day climate estimates were considered as a baseline for comparison with predictions using future climate scenarios, as their rainfall values presented non-significant difference (P value >0.05) in comparison with those obtained using climate datasets from long-term observed data (1917–2016). The datasets generated during the WEPP simulations in different land uses using baseline and projected climates are available as supplementary material (S2).

The multiple comparison test (Tukey) between runoff and soil erosion outcomes for different land uses from simulations using only historical climate statistics (Table 5) repeat for all variables using the downscaled climate from multiple GCMs and RCPs (Table 6). Consequently, land use and management are the most important factors governing runoff and soil erosion rates across different climate inputs and locations (González-Arqueros et al., 2017; Bravo-Espinosa et al., 2009; Mendoza et al., 2010). Additionally, WEPP simulations considering future climate scenarios downscaled for different study sites located in different parts of the world (USA, China, and Ireland) indicate potential significant changes in runoff and soil erosion rates (Garbrecht and Zhang, 2015; Li et al., 2010; Mullan, 2013; Zhang, 2007). In a study located in central-western Brazil (Favis-Mortlock and Guerra, 1999), increases or decreases in predicted runoff and soil erosion may vary depending upon the GCM selected to generate the projected climate used in the WEPP simulations. Therefore, the present study considered climate projections averaged from multiple GCMs, as the models' projection errors might at least be partly reduced using this approach (Tebaldi and Knutti, 2007).

The simulations using projected climate scenarios did not change the differences and similarities between the runoff and soil erosion rates among the land uses considered in this study under subtropical conditions (Table 6). Changes in runoff and soil erosion (Table 7) due to the variations in the rainfall (Fig. 5) occurred at different levels depending on the land use. More details about the relative changes (Δ) in rainfall, runoff and soil erosion for 2030, 2060, and 2090 when compared to baseline predictions are available as supplementary material (S3). Nevertheless, these changes were not significant, even considering the variations in the rainfall which occurred using the RCP 4.5 (2060 and 2090), RCP 6.0 (2030, 2060, and 2090), and RCP 8.5 (2030, 2060, and 2090) climate scenarios, whose changes in rainfall depths were statistically significant (P value <0.05).

Considering the four emissions scenarios (RCPs 2.6, 4.5, 6.0, and 8.5 W m^{-2}) and the projection years (2030, 2060, and 2090), the potential changes in the climatology may not significantly affect the runoff and soil erosion rates, as reported in the simulations (P value >0.05). Therefore, no significant changes in runoff and soil erosion predictions under the projected climates do not mean that those changes are not problematic when comparing them to tolerable thresholds (Mullan, 2013). According to Bertoni and Lombardi-Neto (2012), a general tolerable value for soil loss in the study area is 12 t ha^{-1} yr^{-1}, and this limit was exceeded only by tilled fallow conditions considering all the simulated values. Additionally, the change in annual rainfall depth may increase by up to 113 mm in 2090 considering the worst scenario in terms of greenhouse gas emissions (Table 7). This result agrees with projected rainfall erosivity scenarios reported by Almagro et al. (2017), who also considered the IPCC-AR5 in their methods. However,

Table 6
Rainfall, runoff and soil erosion predictions based on downscaled data from baseline climate (present day).

Land use	Rainfall (mm yr^{-1})	Runoff (mm yr^{-1})	Soil erosion (t ha^{-1} yr^{-1})
Wooded Cerrado	1300	10c	0.09c
Fallow		219a	27.93a
Pasture		90b	0.11c
Sugarcane		19c	0.82b

Identical lower case letters indicate no significant difference between means in the same column by the Tukey means comparison test (P value >0.05).

Table 7
Potential changes (Δ) in rainfall, runoff and soil erosion for 2030, 2060, and 2090 based on downscaled data from multiple GCMs and RCPs in relation to baseline predictions for the present climate.

RCP	Land use	Δ Rainfall (mm yr^{-1})			Δ Runoff (mm yr^{-1})			Δ Soil erosion (t ha^{-1} yr^{-1})			Group		
		2030	2060	2090	2030	2060	2090	2030	2060	2090	2030	2060	2090
2.6	Wooded Cerrado	−4	27	45	1	0	4	0.02	0.07	0.11	F	A	A
	Fallow				8	17	25	0.66	1.08	4.07	A	A	A
	Pasture				1	7	10	0.00	0.01	0.01	A	A	A
	Sugarcane				2	1	4	0.07	−0.04	0.21	A	C	A
4.5	Wooded Cerrado	48	78*	70*	4	−4	−3	0.06	−0.01	−0.03	A	G	G
	Fallow				23	9	7	3.45	0.19	−0.16	A	A	C
	Pasture				10	0	2	0.01	0.00	0.00	A	C	A
	Sugarcane				4	−2	−2	−0.11	0.12	0.05	C	E	E
6.0	Wooded Cerrado	55	56*	74*	3	0	−4	0.06	0.04	−0.01	A	A	G
	Fallow				26	18	14	2.41	0.81	0.26	A	A	A
	Pasture				12	9	5	0.02	0.01	0.00	A	A	A
	Sugarcane				4	3	−4	0.18	0.14	−0.20	A	A	G
8.5	Wooded Cerrado	58*	75*	113*	1	−3	3	0.06	0.05	0.08	A	E	A
	Fallow				30	12	28	1.03	0.91	2.81	A	A	A
	Pasture				10	6	14	0.01	0.01	0.02	A	A	A
	Sugarcane				2	−3	4	0.16	0.06	0.16	A	E	A

Group	Rainfall	Runoff	Soil erosion
A	↑	↑	↑
B	↓	↓	↓
C	↑	↑	↓
D	↓	↓	↑
E	↑	↓	↑
F	↓	↑	↓
G	↑	↓	↓
H	↓	↑	↑

* Indicates a significant change (P value <0.05) in relation to the simulations using the baseline climate (Table 6); RCP: Representative Concentration Pathway (W m^{-2}); results of changes grouped according to the combination of trends (increases and decreases): group A (increases in rainfall, runoff, and soil erosion), B (decreases in rainfall, runoff, and soil erosion), C (increases in rainfall and runoff, and decrease in soil erosion), D (decreases in rainfall and runoff, and increase in soil erosion), E (increases in rainfall and soil erosion, and decrease in runoff), F (decreases in rainfall and soil erosion, and increase in runoff), G (increase in rainfall, and decrease in runoff and soil erosion), and H (decreases in rainfall, and increase in runoff and soil erosion).

the projected changes in rainfall depths had no significant influence on WEPP model predicted runoff and soil erosion, which is different from other cases in the literature for other locations, in which most of the changes were statistically significant (Garbrecht and Zhang, 2015; Li et al., 2010; Nearing et al., 2004).

We found all of the eight possible combinations (groups) of trends in changes for rainfall, runoff, and soil erosion present. The RCP 2.6 presented a no change in the rainfall by 2030, followed by non-significant increases by 2060 and 2090. Changes of this kind were also reported in the study by Li et al. (2010), whose simulations using WEPP also

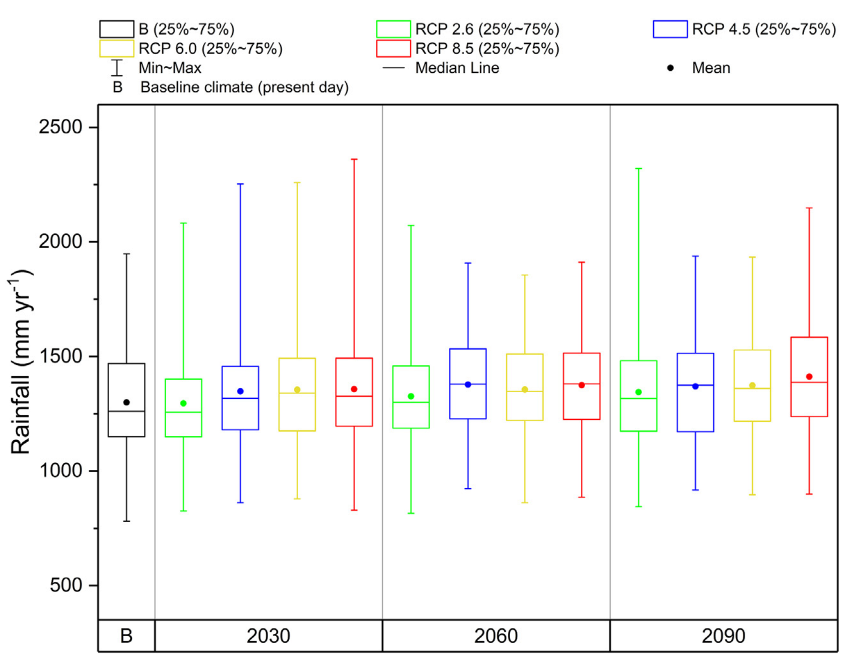

Fig. 5. Rainfall variability considering baseline (present day) climate and different climate changes scenarios (RCPs 2.5, 4.5, 6.0, and 8.5 projected to 2030, 2060, and 2090).

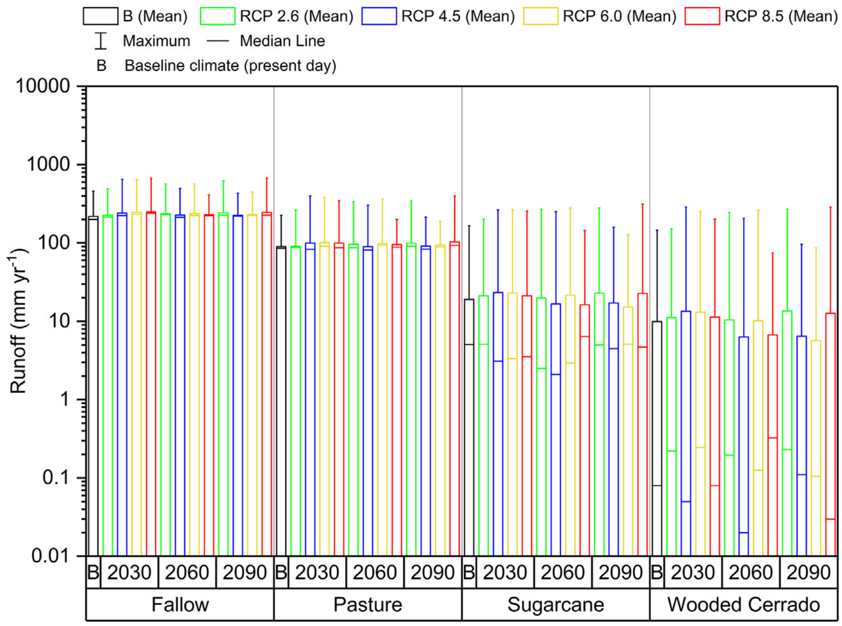

Fig. 6. Runoff considering baseline (present day) climate and different climate changes scenarios (RCPs 2.5, 4.5, 6.0, and 8.5 projected to 2030, 2060, and 2090) on four different land uses.

revealed impacts on crop yields under different climate change scenarios. The simulations using the RCP 4.5, 6.0, and 8.5 showed significant increases in rainfall and variable behaviors for runoff and soil erosion. Overall, the main behavior was in group A, which occurred mainly with the most drastic scenarios, related to the greenhouse gas emissions increasing with time (RCPs 6.0 and 8.5). Sugarcane and wooded Cerrado had greater relative changes in runoff and soil erosion, while pasture and fallow were less sensitive to the variations in the rainfall. These greater relative changes in sugarcane and wooded Cerrado may happen due to the more variable soil cover through the year related to the plants' seasonality (wooded Cerrado), cycle (sugarcane), and management (sugarcane), as mentioned before in Section 3.2.1. Meanwhile, sugarcane exhibited a singular behavior in relation to the other land uses (groups C, E, and G), presenting slight decreases in predicted runoff and soil erosion with increases in precipitation and air temperatures in a number of future projections. These factors may increase sugarcane biomass production in Southeastern Brazil within these future climate scenarios (Marin et al., 2012), and consequently, this may prevent increased values for runoff and soil erosion.

The differences in the orders of magnitude of the runoff for each land use were smaller than the ones found for the soil loss simulations. The runoff behavior, as reported in a previous study (Oliveira et al., 2016), had the tilled fallow conditions generating a higher amount of overland flow, followed by pasture, sugarcane, and wooded Cerrado, respectively. We observed great variability in the range of the simulations when all the climates (present and future) under the different emissions levels (RCPs) were considered (Fig. 6).

The predicted soil erosion rates fell into lower ranges, but the tilled fallow conditions resulted in soil loss at a higher order of magnitude than the other land uses (wooded Cerrado, pasture, and sugarcane)

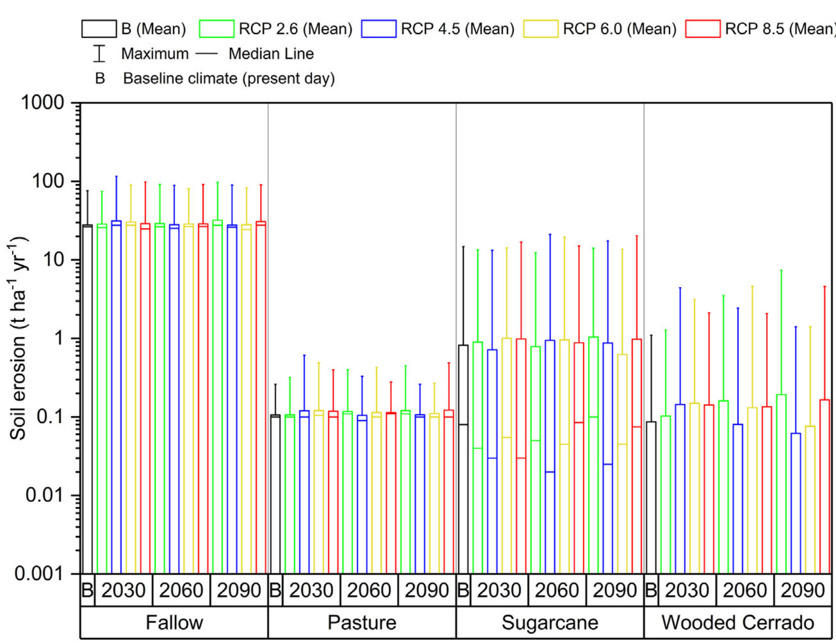

Fig. 7. Soil erosion considering baseline (present day) climate and different climate changes scenarios (RCPs 2.5, 4.5, 6.0, and 8.5 projected to 2030, 2060, and 2090) on four different land uses (median lines does not appear on wooded Cerrado as they are equal to zero).

and, when future scenarios were included in this kind of prediction, a rise in the uncertainties may be expected (Favis-Mortlock and Guerra, 1999; Vanwalleghem et al., 2017). As discussed by Oliveira et al. (2015), the responses of natural and undisturbed conditions such as wooded Cerrado in terms of soil loss were very low in comparison to conventional crops. However, this study demonstrated that pasturelands might produce as much sediment as an undisturbed land similar to a wooded Cerrado area (Fig. 7). Additionally, this study confirms that crop expansion (such as sugarcane) into the Brazilian Cerrado biome can increase total soil erosion in Brazil significantly (Merten and Minella, 2013).

4. Summary and conclusions

We presented the responses of runoff and soil erosion to different land uses and climate change in a subtropical area inside the Brazilian Cerrado biome. This study calibrated and validated the WEPP model based on experimental data from field plots constructed for runoff and soil erosion observations. The optimized parameters for the WEPP model were consistent with measured soil characteristics and to the land use and management present at the site. Therefore, the WEPP model can be used under subtropical conditions when it is calibrated.

The preliminary simulations using a stochastically generated climate input reveal that land use can change the patterns of the runoff and soil loss rates. The runoff behavior was distinct for all land uses, but for soil loss, there were relevant similarities between pasture and undisturbed wooded Cerrado, suggesting that management following conservation principles may result in soil sustainability.

Possible future climate scenarios may increase the variability of runoff and soil erosion. On the other hand, no significant changes in the rates were observed in our simulations. In spite of this fact, under the major and significant increases in rainfall through the worst projected climate change scenario, the predominant trends of the runoff and soil erosion responses were to increase for almost all land uses (wooded Cerrado, tilled fallow, and pasture), except for sugarcane, which may have slight decreases in runoff and soil loss. Increased biomass production and cover in the sugarcane due to elevated temperatures and rainfall may offset any increased runoff and erosion potential due to the increased precipitation.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2017.11.257.

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